Searching for warm-hot intergalactic medium in emisison

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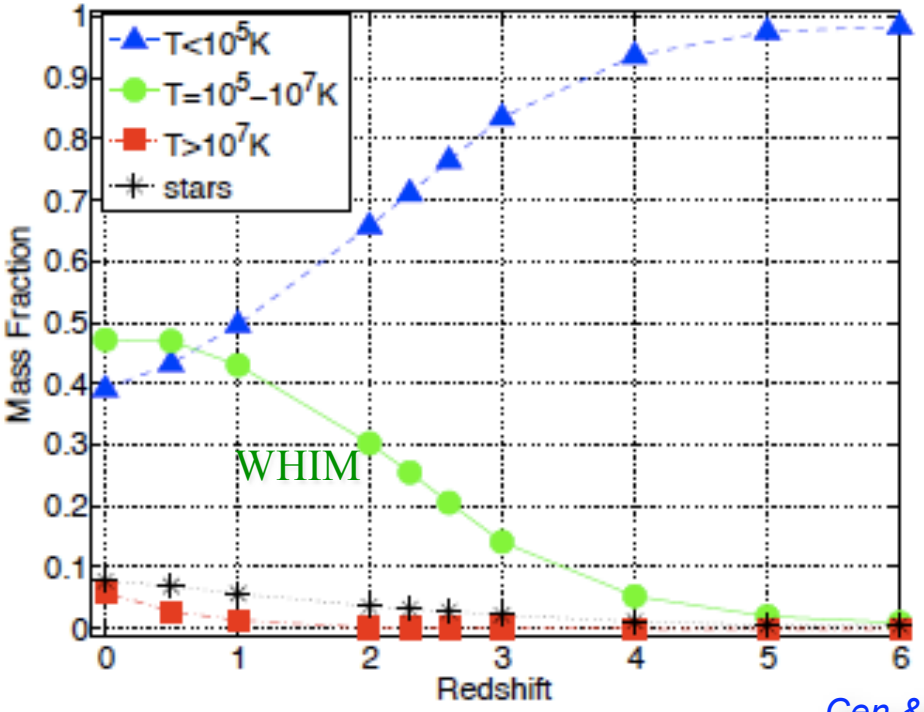
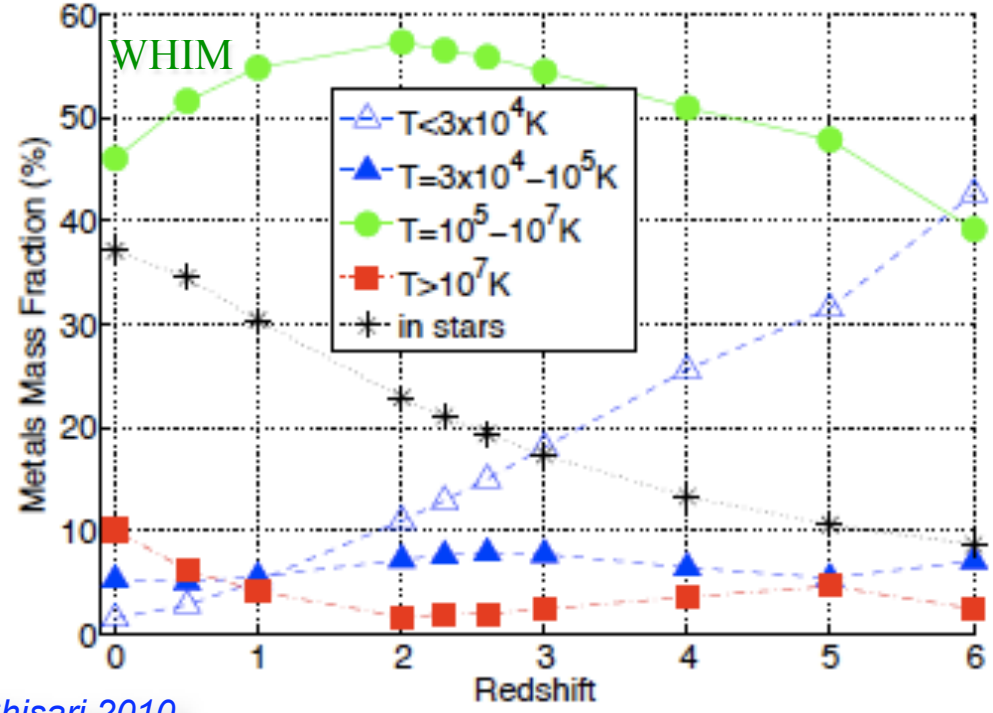
Warm-hot intergalactic medium and CCE

- Warm-hot intergalactic medium (WHIM):
  - T=10^5-10^7 K; $n_{\rm H}$ = 10^{-5}-10^{-3} cm^{-3}.
- Dominant mass and metal reservoir at z=0.
- Chemical enrichment history is imprinted.

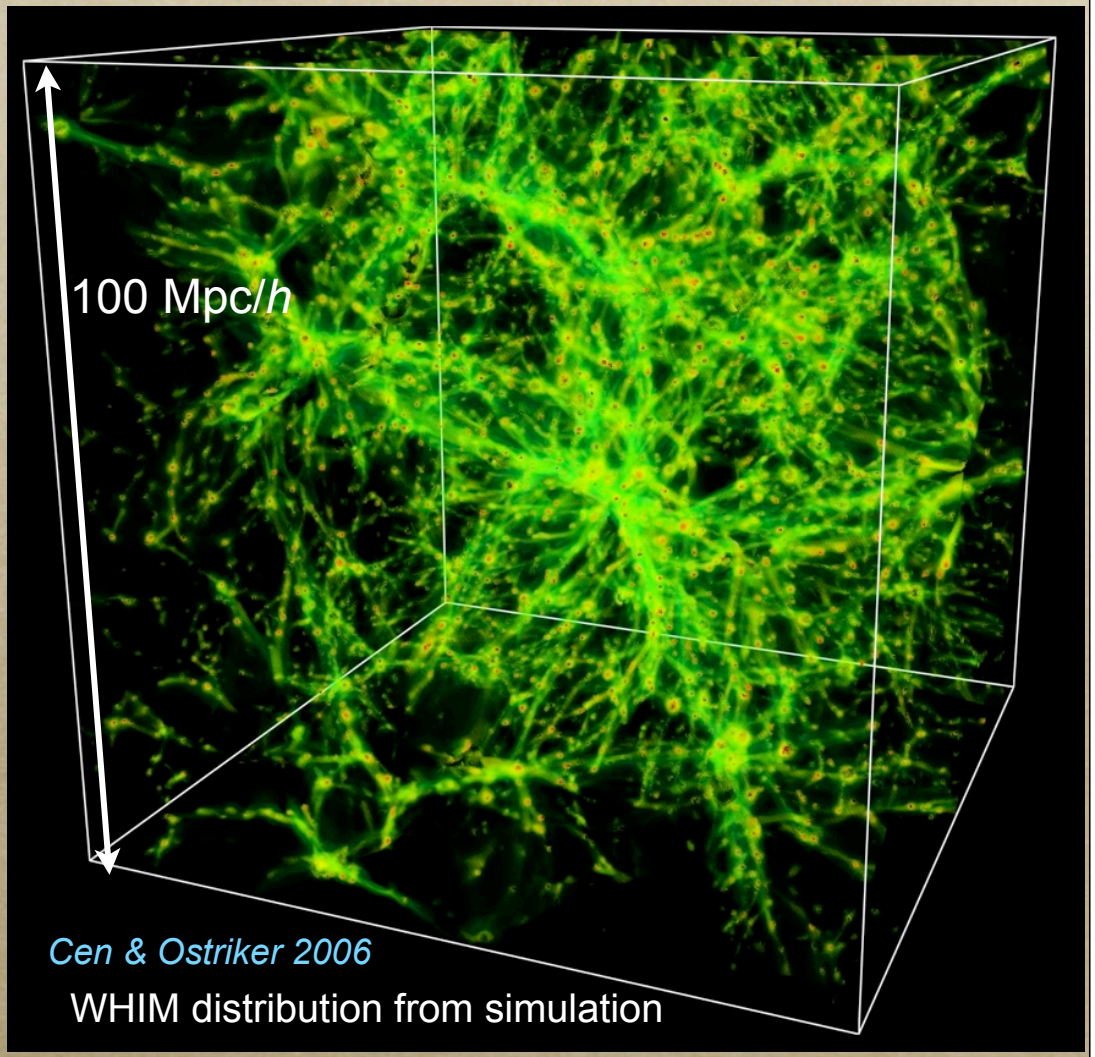




Cen & Chisari 2010

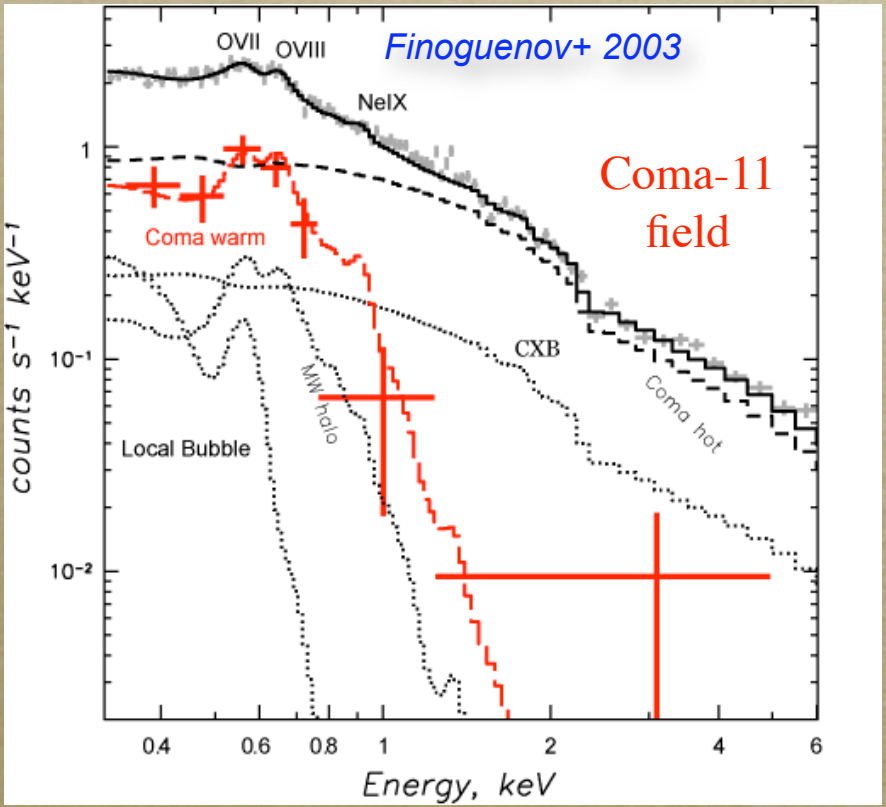
Why do we search in emission?

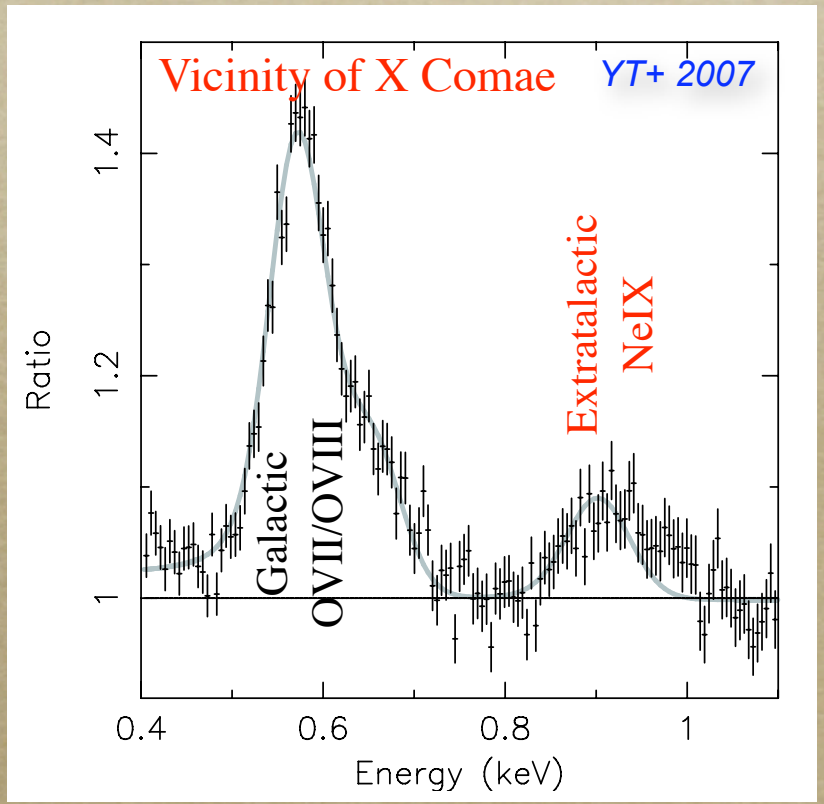
- Emission may give us 3D distribution of the WHIM.
  - Absorption can only do pencil beam analysis.
- Interaction to dense nodes (clusters) may be studied.
- Applicable for only dense region ($I \propto n_{\rm H}^2$)
  - Absorption can probe less density region ($EW \propto n_{\rm H}$)



Report of WHIM emission in cluster vicinities

- Possible detection for several clusters (Kaastra+ 2003)
- Strong OVII/OVIII emission in Coma-11 field (Finoguenov+ 2003)
- NeIX emission signature in vicinity of X Comae, associated with NeIX absorption (3σ; YT+ 2007)

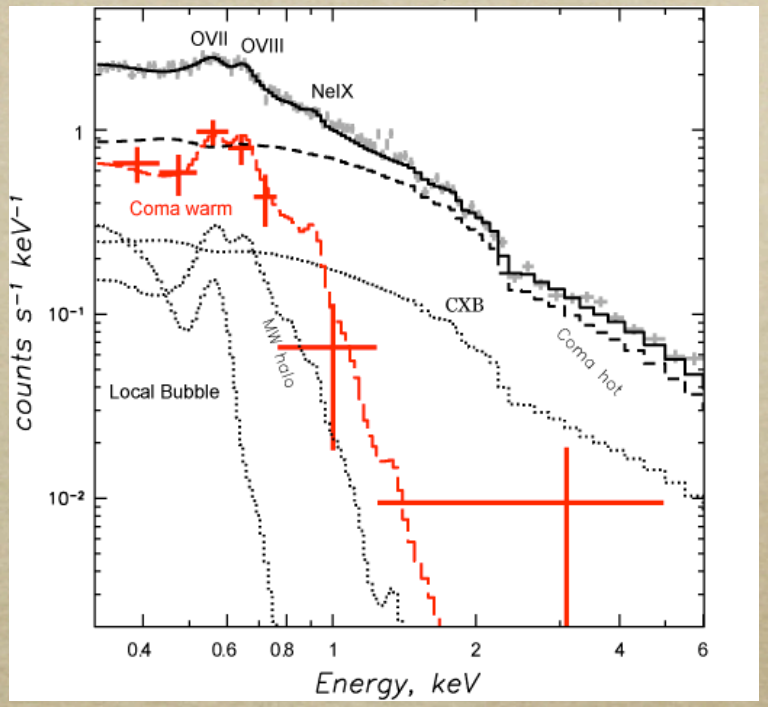


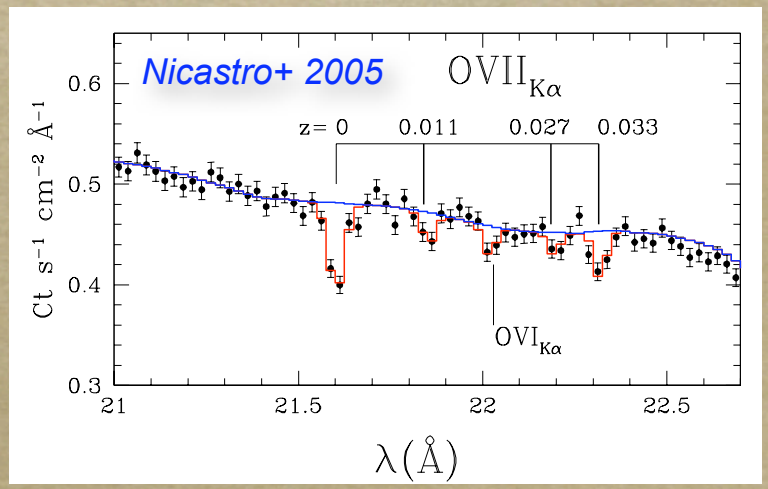


Old good days... (looked quite promising)

- Around 2003-2005, *many* detections are reported.
  - Kaastra+ 2003
  - Finoguenov+ 2003
  - Nicastro+ 2005 (absorption)

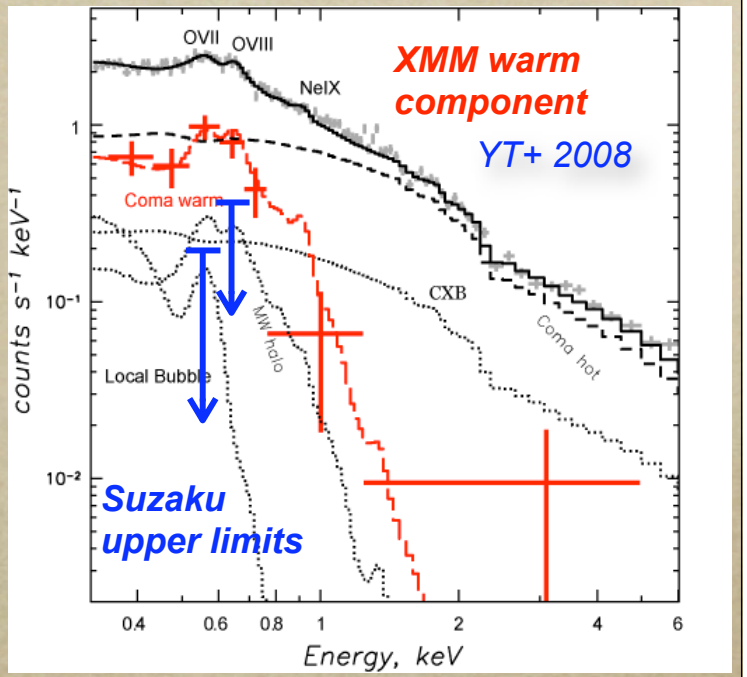
- First X-ray microcalorimter on Astro-E2 (Suzaku) was about to be launched (2005), which enables first imaging (fine) spectroscopy.

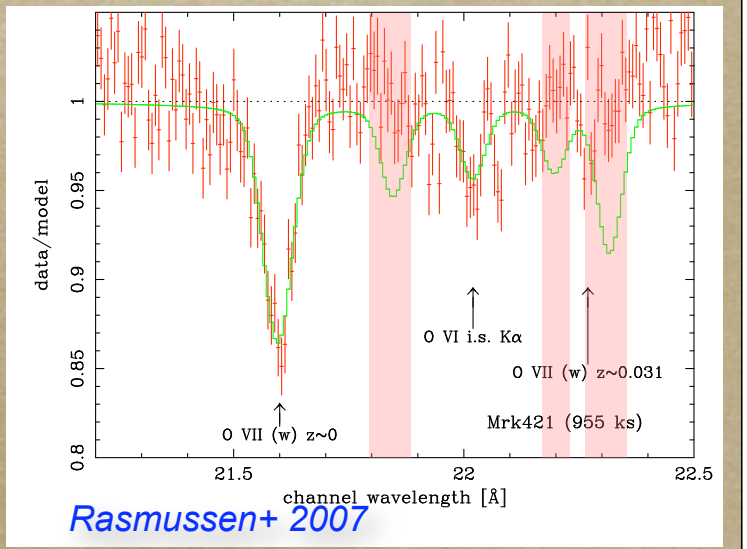




After a couple of years… (reality not so easy)

- It turned out that the detections are not WHIM.
  - Kaastra+ 2003
    - ***Calibration and Galactic foreground problem.***
  - Finoguenov+ 2003
    - ***Solar wind charge exchange (YT+ 2008).***
  - Nicastro+ 2005 (absorption)
    - ***Not confirmed by XMM (Rasmussen+ 2007, Kaastra+ 2007).***
- First X-ray microcalorimter on Astro-E2 (Suzaku) did not succeed observations.
  - ***Not achieved due to unexpected He loss.***



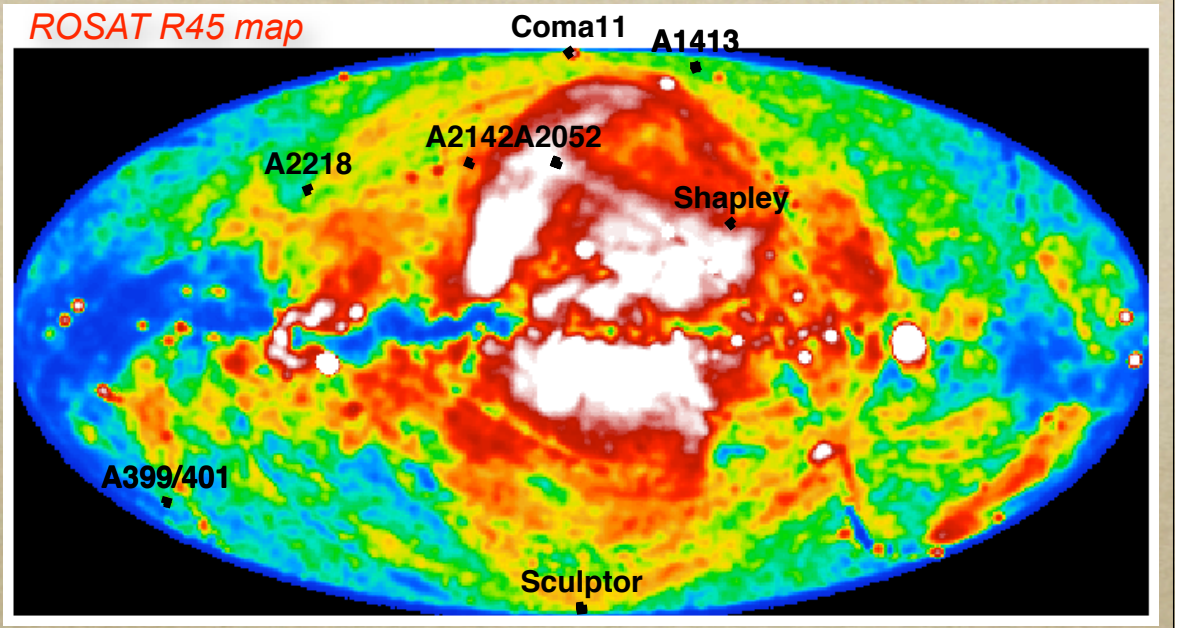


Search for WHIM in emission

- Two approaches
  - CCD-based search using a current mission.
    - Search for *redshifted* OVII and OVIII lines to get "evidence" of WHIM.
    - We use *Suzaku* because it has low and stable detector background and line spread function at low energy is good.
  - Proposing new mission with a microcalorimeter.
    - DIOS (Japan), XENIA (US, Europe, Japan)
    - Estimating detectability is important.

Search cluster vicinities with *Suzaku*

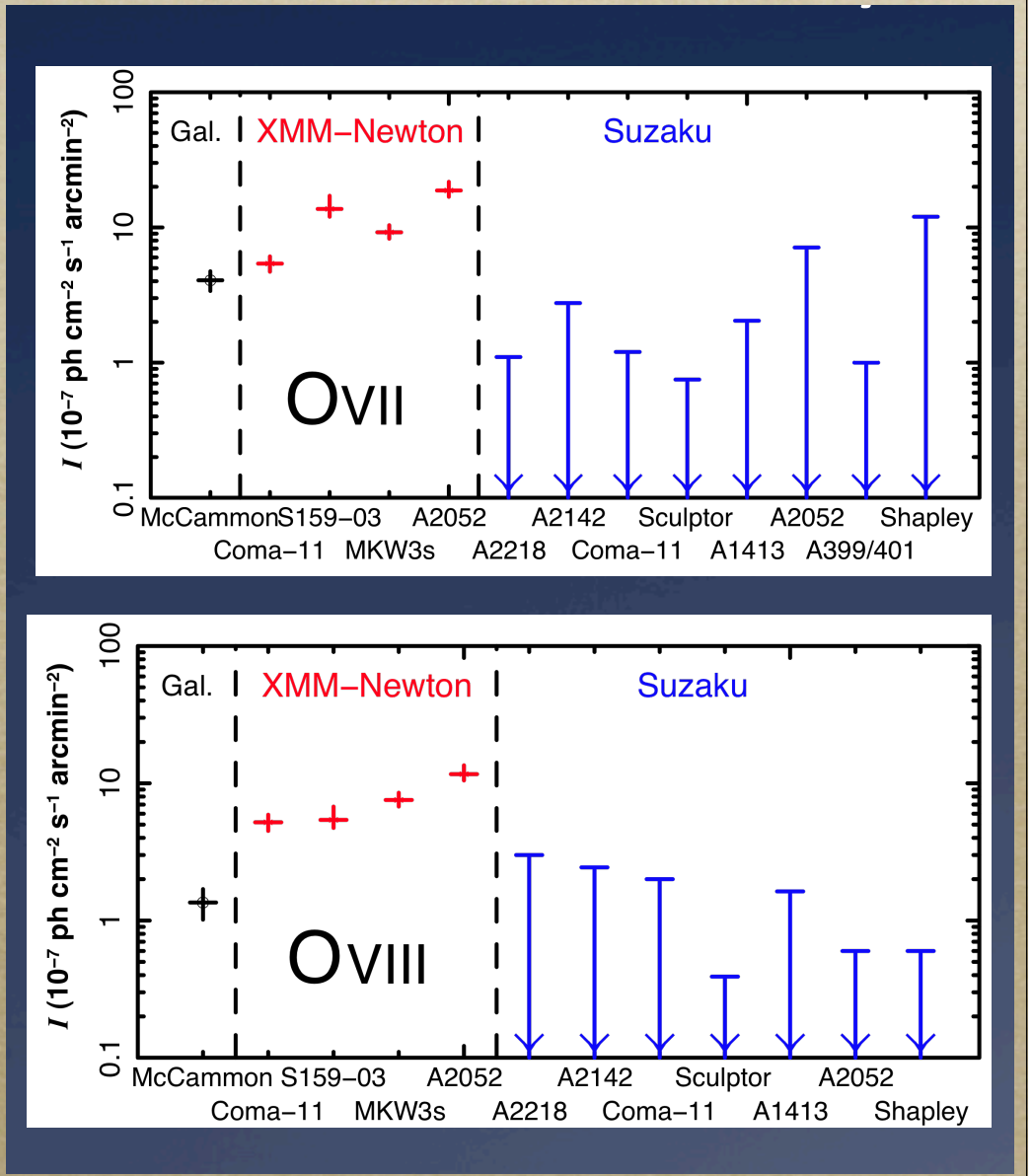
- Eight clusters and superclusters have been observed.
  - Targets are selected based on the possible elongation in LOS and reported soft emission in literature



Target	Redshift	Info	Observation	Reference
A2218	0.18	Elongation in LOS is suggested	2005-10-27	YT+07
Coma-11	0.02	XMM detected OVII/OVIII liens	2007-06-21	YT+08
A399/401	0.07	Pair cluster	2006-08-22	Fujita+08
A2052	0.04	Soft excess reported with XMM	2005-08-20	Tamura+08
A1413	0.14	Suzaku observed to virial radius	2005-11-15	Hoshino+10
A2142	0.09	Big cluster under merger	2007-01-05	Akamatsu+ in prep.
Shapley	0.06	Soft excess reported with ROSAT	2008-07-10	Mitsuishi+ in prep.
Sculptor	0.11	Soft excess reported with ROSAT	2005-12-03	Sato+ in prep.

Search cluster vicinities with *Suzaku* 2

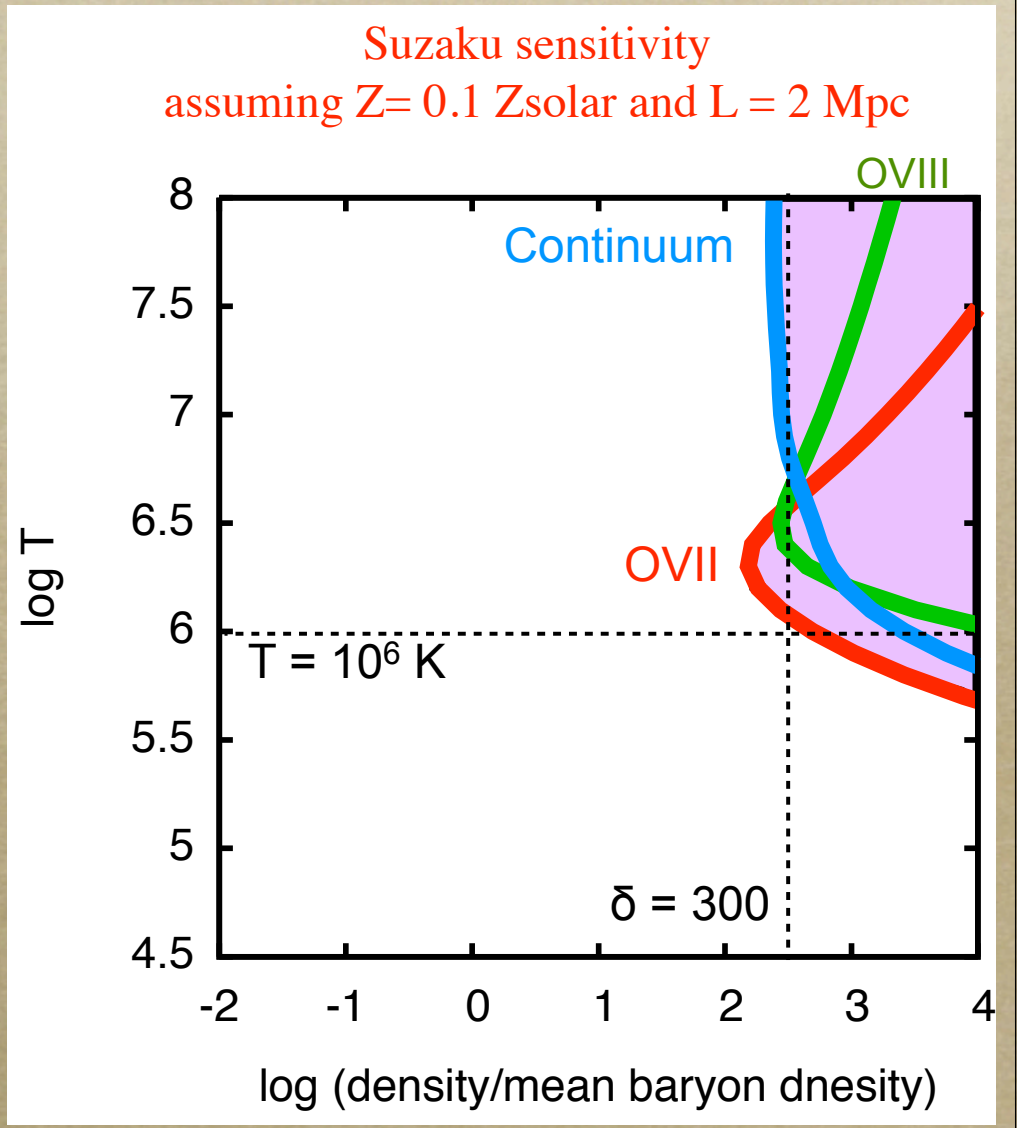
- No detection. Tight upper limits of OVII/OVIII surface brightness is obtained.
- Some upper limits are tighter than previously claimed "detections".
- Discrepancy mainly due to incorrect foreground modeling. (c.f. Mitsuda talk yesterday)



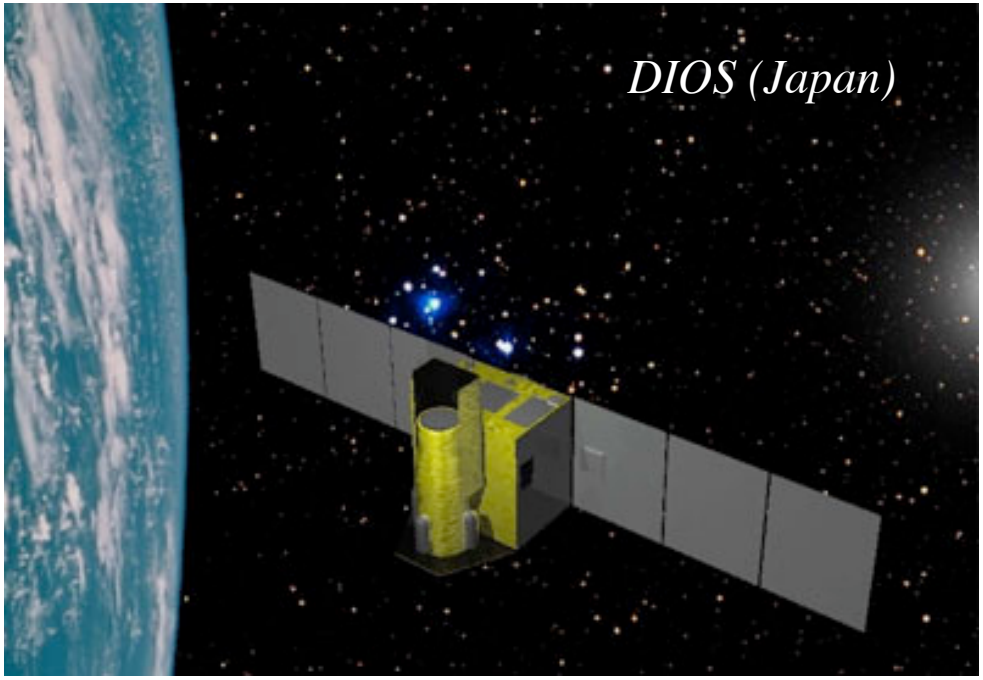
Estimated upper limit of overdensity

$$I \propto \int n_{\rm H} n_{\rm e} Z F(T) dL$$
$$\propto n_{\rm H}^2 Z L F(T)$$

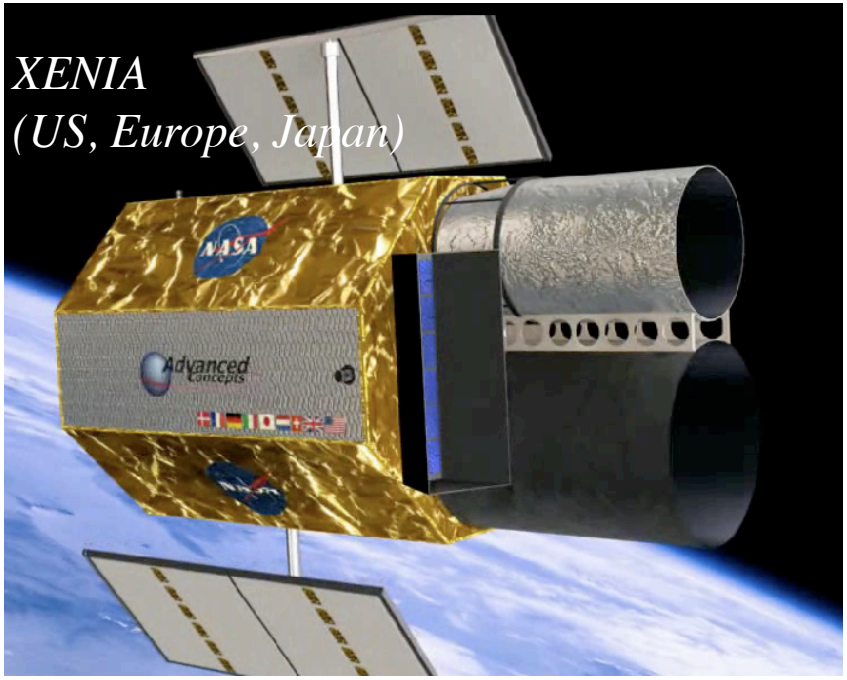
- Surface brightness is proportional to density^2, abundance (Z), LOS path length (L) and emissivity ($F(T)$).
- Density is constrained with an assumption of Z, L and T.
- Suzaku upper limits correspond to δ~300 assuming $Z = 0.1\ Z_{\rm solar}$ and $L = 2$ Mpc



Future missions optimized for WHIM study



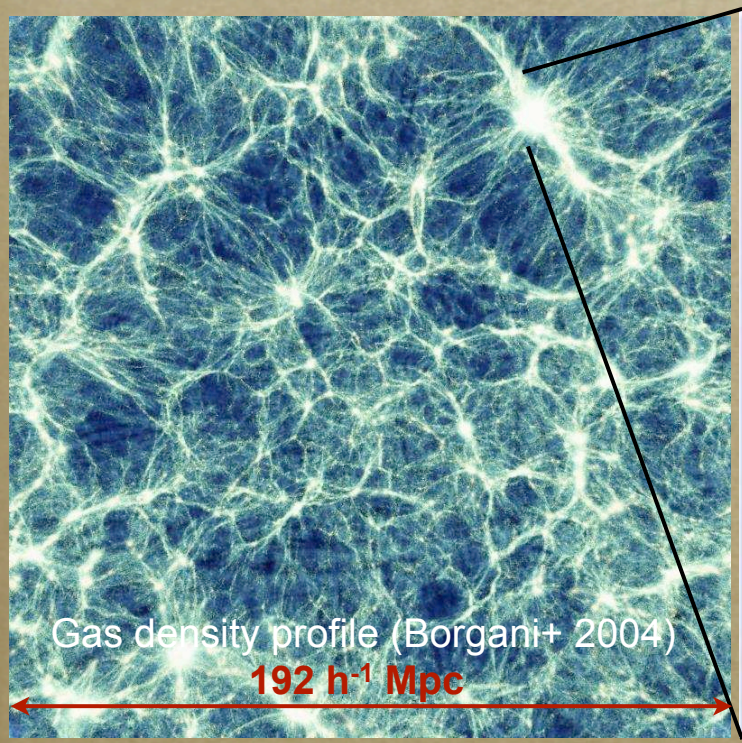
- Δ E: 2 eV
- Effective area: ~100 cm^2
- *N* of pixels: 12 x 12 pixels
- FOV: 0.7 deg x 0.7 deg
- PSF: 2 arcmin HPD

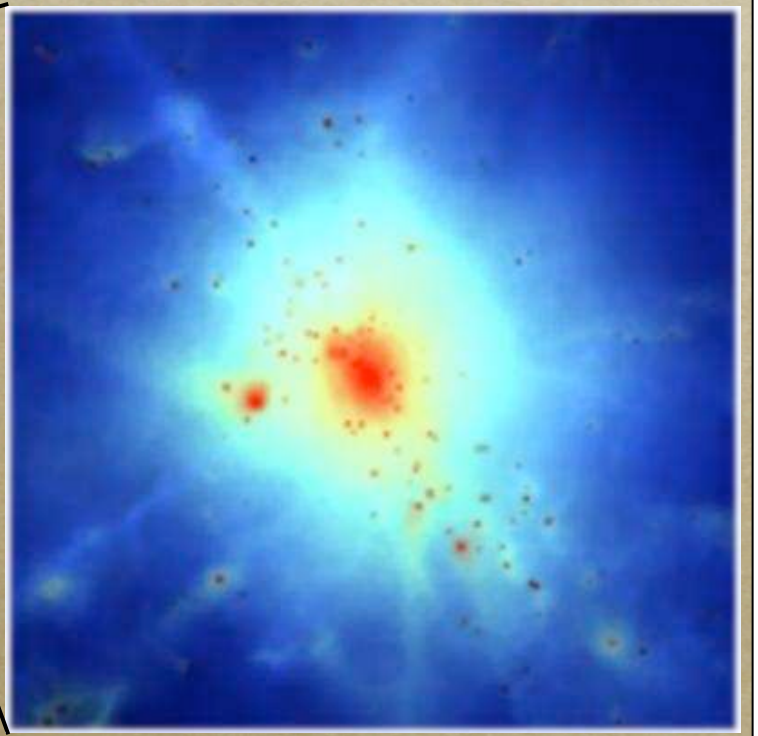


- Δ E: 2.5 eV (goal 1 eV)
- Effective area: ~1000 cm^2 (goal 1300)
- *N* of pixels: 2000 (goal 2176)
- FOV: 0.9 deg x 0.9 deg (goal 1 x 1)
- PSF: 4 arcmin HPD (goal 2.5)

Simulation for detectability with XENIA

- Studied mock spectra based on SPH simulation by Borgani+ 2004, based on GADGET-2 (Springel+ 2005)
- Spectrum is calculated assuming CIE.
- Metallicity is determined a posteriori, (either as min(0.3, 0.005(ρ/<ρ>) (Croft+ 2001) or as that with scatter to reproduce Cen & Ostriker 1998).



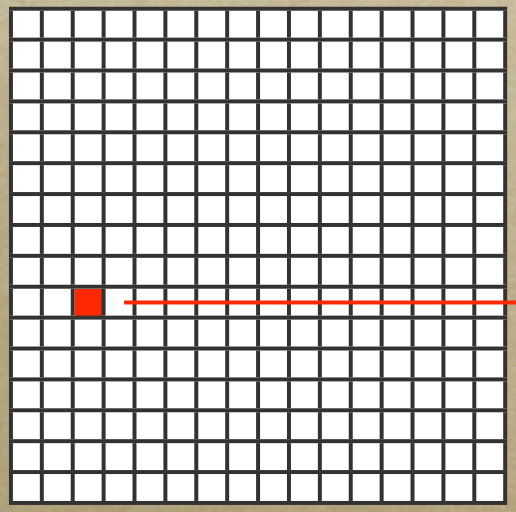


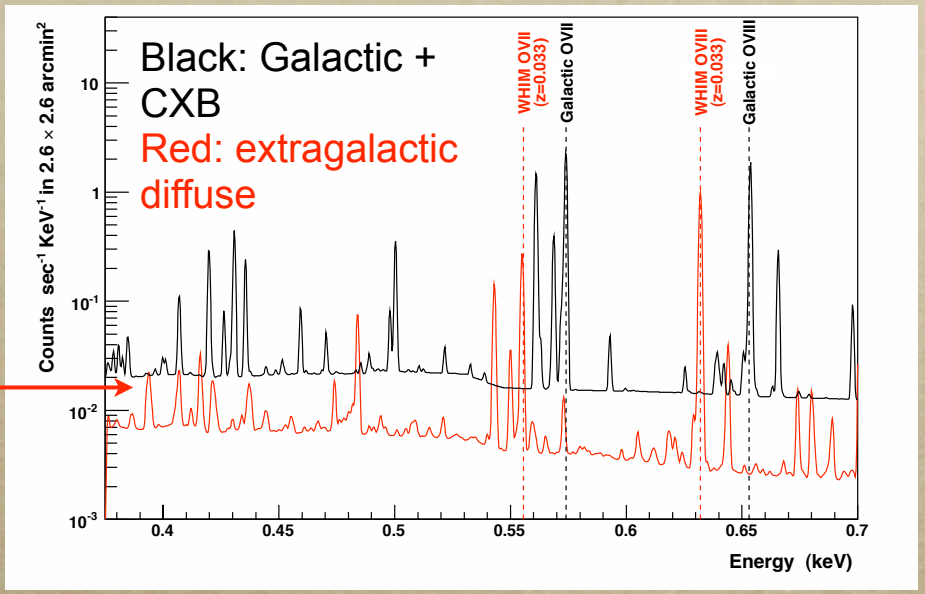
- $\Omega_\Lambda = 0.7$
- $\Omega_b = 0.04$
- $h = 0.7$
- $\sigma_8 = 0.8$
- Box size = $192h^{-1}$ Mpc
- particles = $480^3 + 480^3$
- Gravitatioal softning: $\varepsilon = 7.5h^{-1}$ Mpc at z=0.
- SF: included as sub-resolution multiphase mode (Springel & Hernquiet 2003)
- FB from SNe: weak galactic outflows
- Radiative cooling assumes zero metallicity

Detecting emission lines from mock spectra

- Created mock spectra for 0<z<0.5 gas, for each 2.6'x2.6' angular size.
- Detection is based on pixel-by-pixel (2.6'x2.6') spectrum
- XENIA goal: ΔE = 1 eV, t_{exp} = 1Ms gives 0.07 ph s^{-1} cm^{-2} sr^{-1} as the 5σ detection limit.

Detector (CRIS)



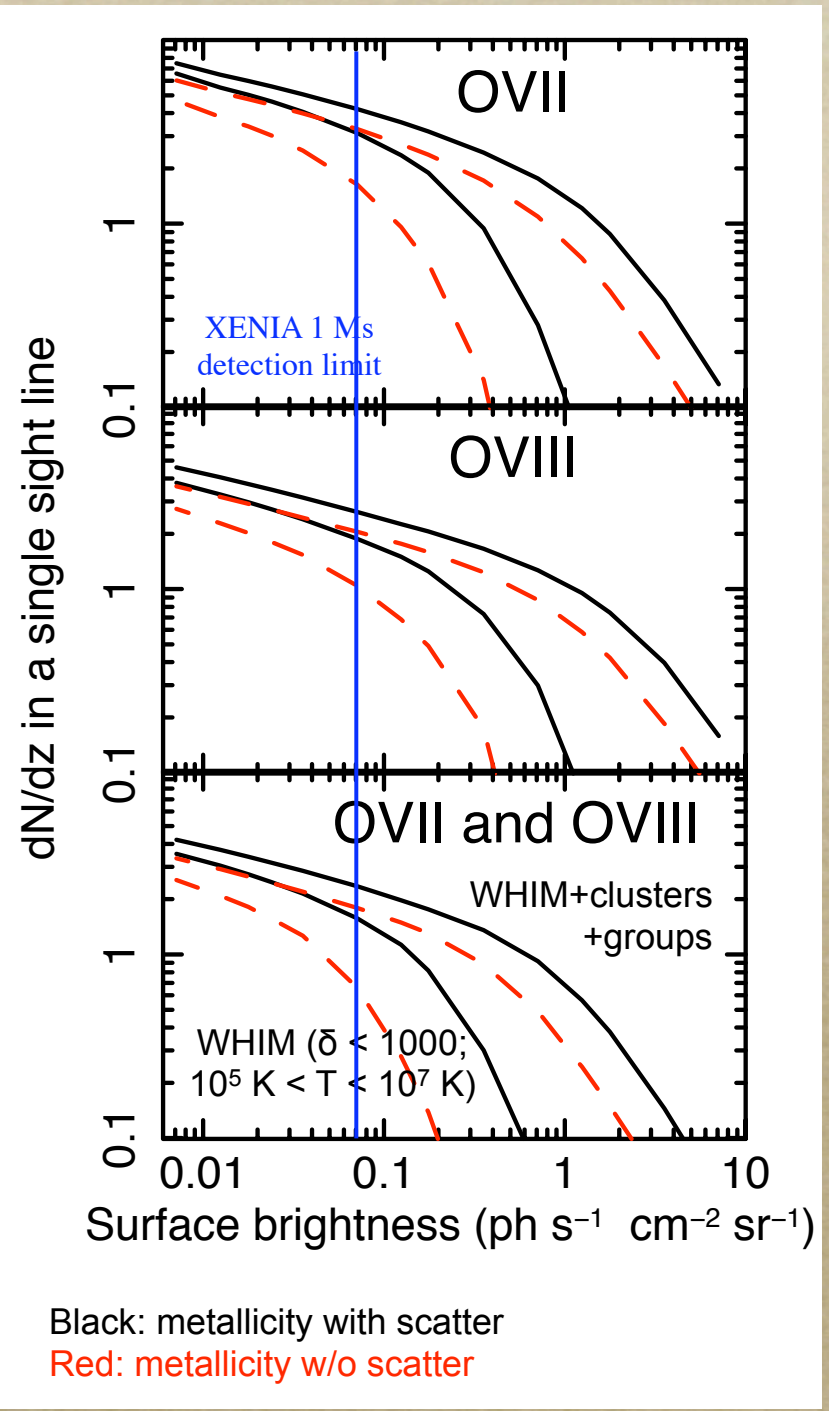


$$\sigma_{\rm line} = \frac{f_{\rm line}}{\sqrt{[f_{\rm line} + (f_{\rm CXB} + f_{\rm FG})\Delta E]}} \sqrt{\Delta\Omega t_{\rm exp} A_{\rm eff}},$$

30 ph s^{-1} cm^{-2} keV^{-1} sr^{-1} — 20 ph s^{-1} cm^{-2} keV^{-1} sr^{-1} — 1 eV — 2.6' x 2.6' — 1 Ms — 1000 cm^2 (XENIA)

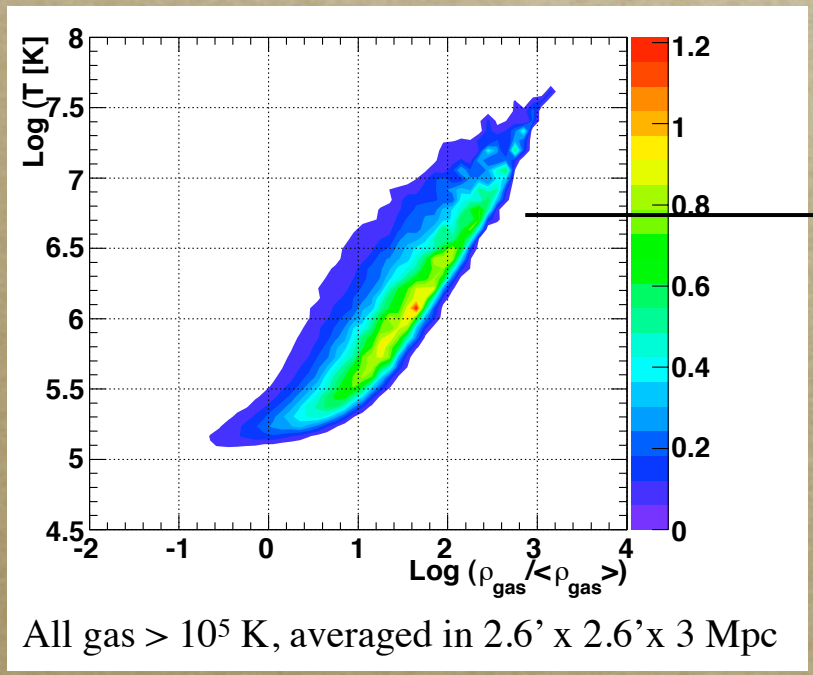
Detectability with XENIA

- Expected detection is dNdz > 1 for both OVII and OVIII lines for a single sight line.
- With 1 deg x 1 deg FOV, dz = 0.5, and 2.6‘x2.6’ angular element size, More than 600 OVII/OVIII pairs are expected to be detected with one 1 Ms observation.
- Metallicity difference makes a factor of ~2 difference.

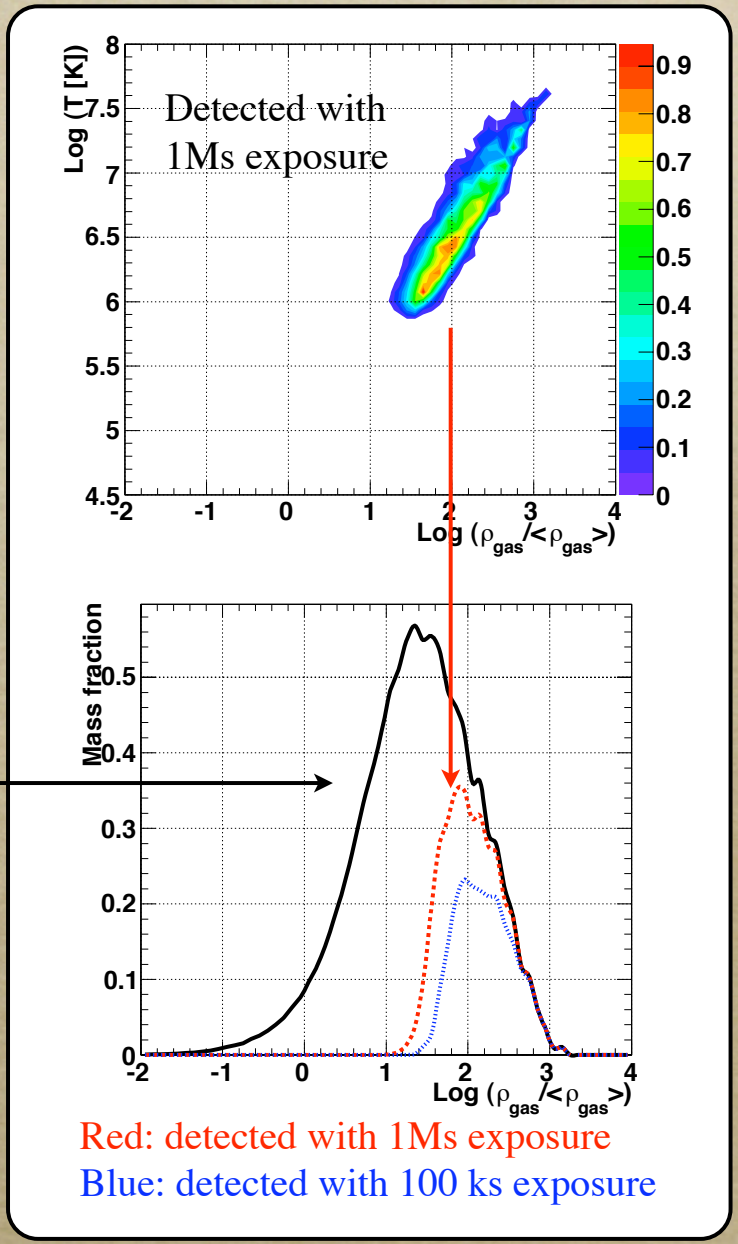


Probed WHIM in ρ-T space

- Based on pair detection of OVII and OVIII.
- Most of δ>100 and half of δ>30 region can be probed.
- Metallicity with scatter assumed.



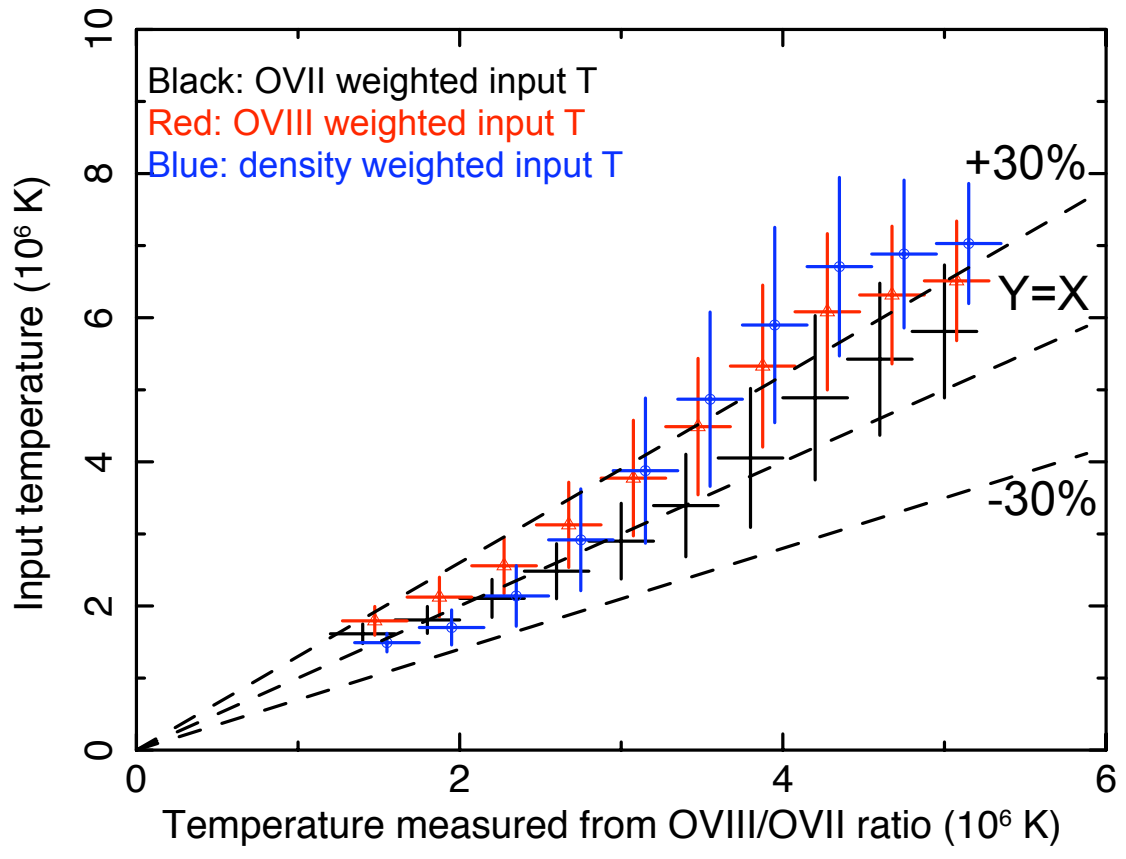
All gas > 10^5 K, averaged in 2.6' x 2.6'x 3 Mpc



Red: detected with 1Ms exposure
Blue: detected with 100 ks exposure

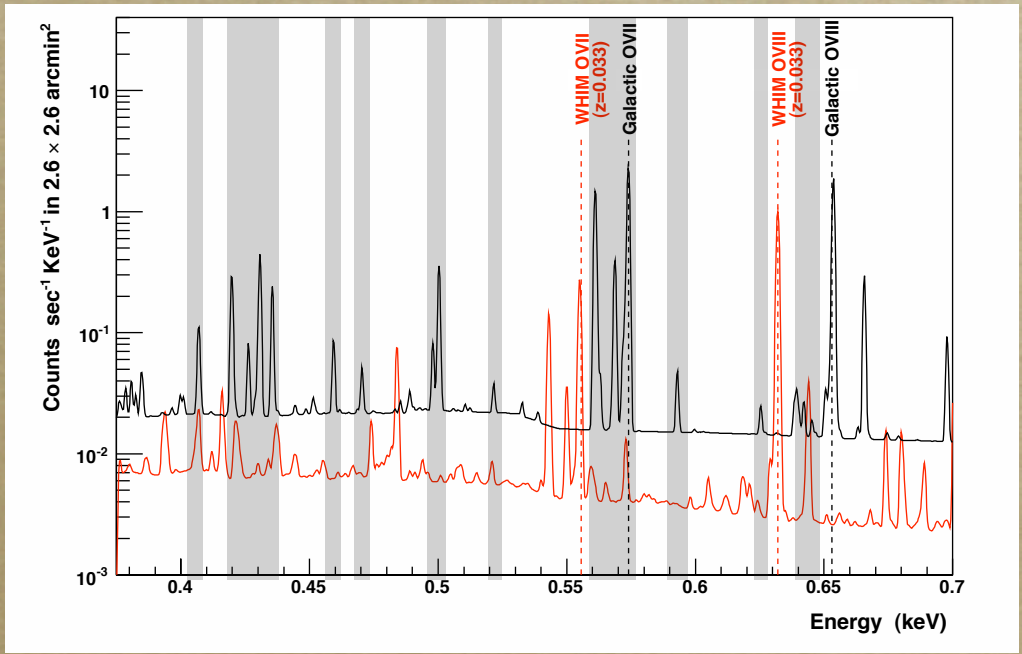
Temperature estimate from mock observation

- Quite good correlation.
- The temperature of the region can be estimated from OVIII/OVII ratio by ~30% uncertainty.
- Matches best to OVII emissivity weighted temperature.



Identification of OVII and OVIII pairs.

- How good the 3D map is created depends on how good we identify emitters.
  - A single line cannot determine redshift, because we do not know a priori what the line is.
    - OVIII and OVII "pairs" can be identified using energy ratio of lines.
  - Careful exclusion of foreground lines and distinction of other (e.g., Fe L complex) lines are essential.
- 70% of the emitters can be identified. Spurious detections are no more than 10%.

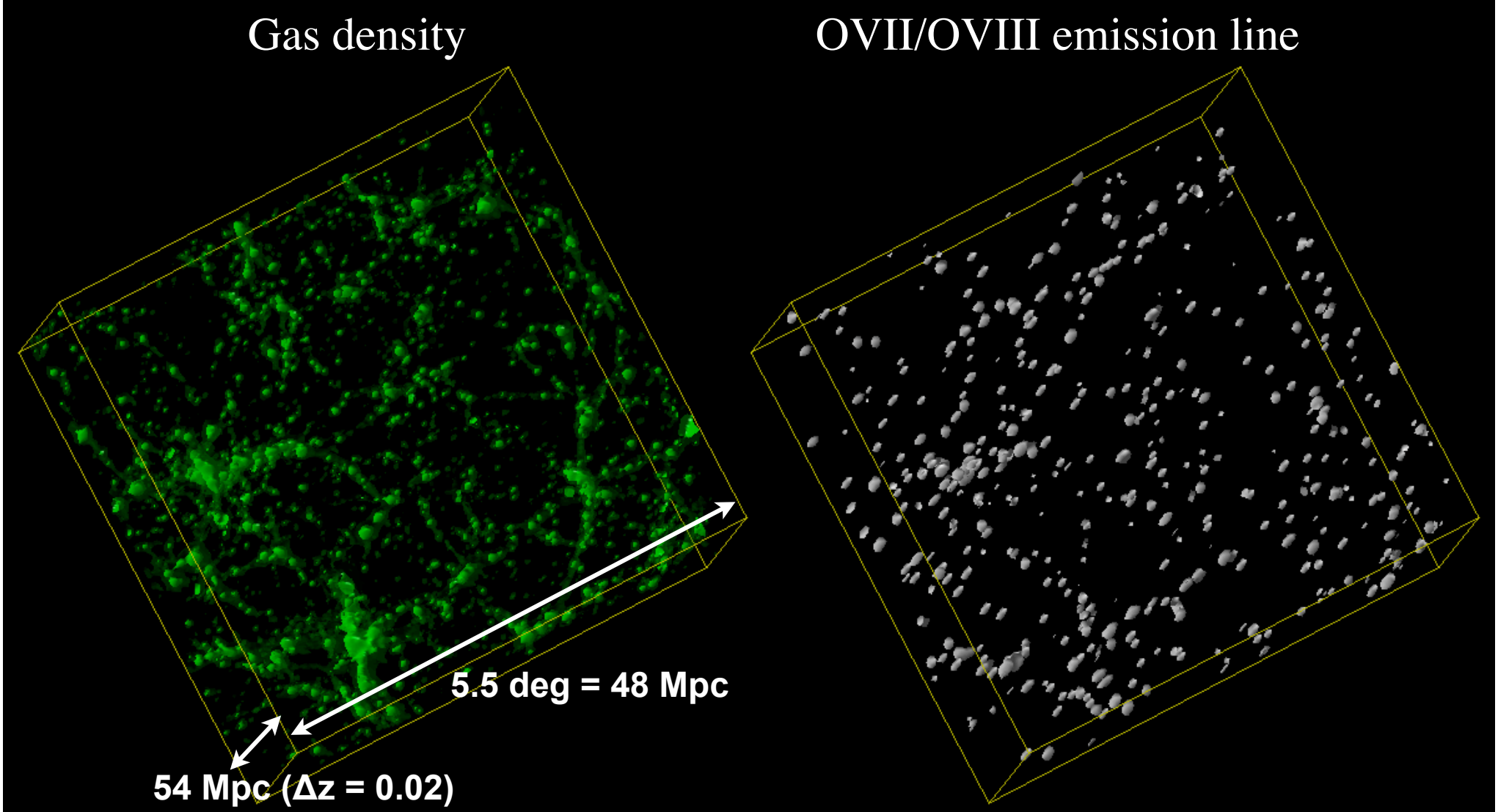


Black: Galactic + unresolved extragalactic sources
Red: extragalactic diffuse

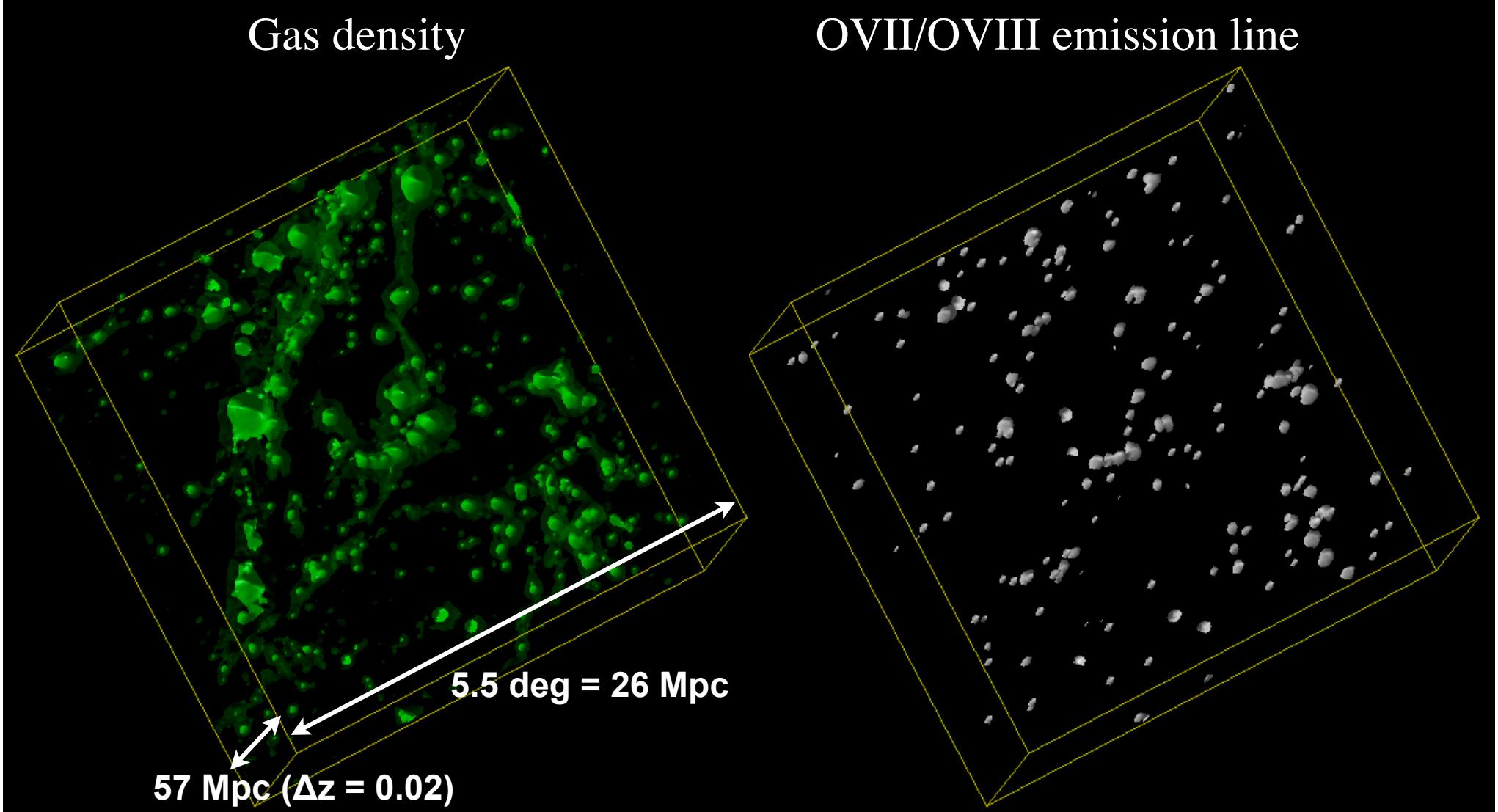
Galactic components: absorbed CIE plasma + unabsorbed CIE plasma. SWCX is spectrum is not taken into account.

Detector energy resolution of 1 eV.

Expected 3D map at z=0.22



Expected 3D map at z=0.1



Prospects with other missions

- Suzaku
  - Sensitivity reaches to δ~300. Possibly we will get evidence of redshifted O lines for a few cluster outskirts
- DIOS
  - Similar energy resolution, but x10 smaller effective area as XENIA.
  - Expected to provide similar 3D maps as XENIA. However, only denser nodes can be probed.
- Astro-H (2014)
  - First microcalorimeter in orbit. But small effective area (100 cm^2) and small FOV (2.9'x2.9') limits the study at cluster outskirts/groups.
- IXO
  - Quite larger effective area (x10), but small FOV (x1/1000). Good to probe smaller scale blobs, but not suitable for mapping. For absorption study, IXO will provide a significant progress.

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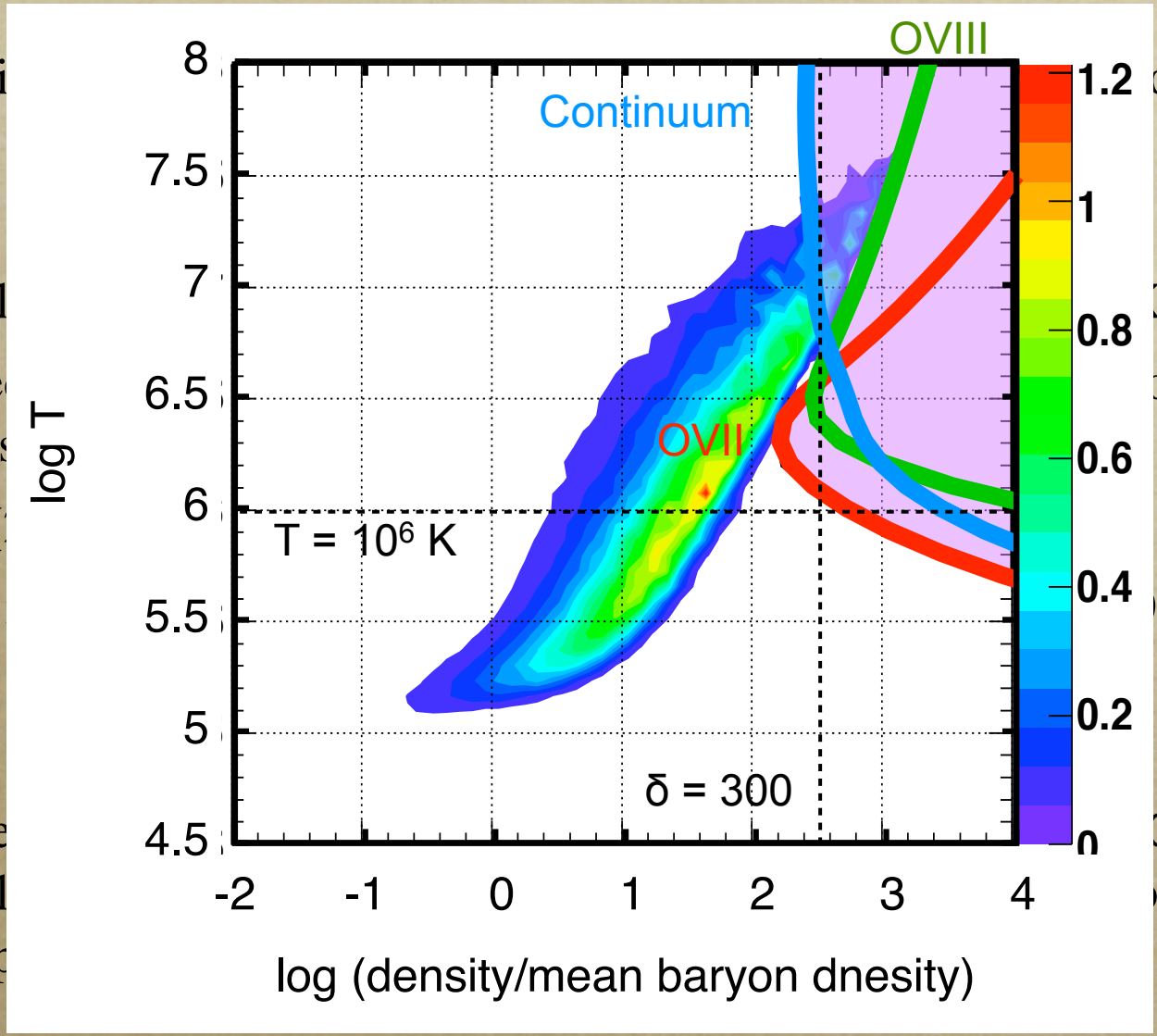

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Summary

- WHIM study using emission still remains to be done.
  - No significant detection yet.
  - Will be a new probe for cosmic chemical evolution.

- XENIA will certainly make a remarkable progress.
  - ~600 OVII/OVIII pairs in a 1 Ms exposure.
  - Half of mass of δ~30 detected.
  - Temperature determination with ~30% error.
  - 3D maps.

- CCD-based analysis (*Suzaku*) is quite tough, but maybe detect a few redshifted O lines associated with the large scale structure.